AR and HRC integration for Enhanced Pragmatic Quality

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***Abstract*— In the landscape of modern manufacturing, Human-Robot Collaboration (HRC) has evolved to be an indispensable element in facilitating synchronized task execution between humans and their robotic counterparts. The infusion of augmented reality (AR) into HRC, particularly in AR-integrated assembly procedures, introduces a promising dimension to the assembly process. This research examines whether AR-enhanced assembly procedures can facilitate HRC. Central to our investigation is the operational implications and the potential enrichment of the operator's pragmatic quality. Our distinct methodological approach puts the spotlight on the holistic experience of operators in AR-integrated HRC scenarios. Our results underscore the AR assembly procedure's notable benefits in terms of increased effectiveness, elevated user satisfaction reinforcing its value in HRC contexts.**

Keywords—Human--robot Collaboration, Augmented Reality, Pragmatic

I. INTRODUCTION

In light of the escalating demand for bespoke product configurations, the ability to flexibly address and oversee a variety of consumer preferences, termed as manufacturing adaptability, has become imperative to manufacturers [1]. Conventional robotic systems, conceived for elevated throughput yet minimal diversity in production, often struggle to accommodate the burgeoning prerequisites of limited volumes yet elevated personalization [2]. Contemporary intelligent manufacturing facilities necessitate integrated configurations where the human workforce and robotic entities synergize [3]. However, a substantial proportion of scholarly work on HRC seems to have a stronger emphasis on the robotic aspect, primarily tackling technological issues and their solutions, while the human aspect [4], such as user experience (UX) considerations [3], has been left largely under-addressed.

Similar to all interactive systems, a favorable UX is imperative for robots to realize their intended advantages. Negative engagement with a robot may lead to aversion to robot interactions, potentially hindering the acceptance of forthcoming robotic innovations [5]. According to prior studies in the realm of UX, the user experience is delineated by a system’s pragmatic (often termed as 'instrumental product', 'task-focused', or 'ergonomic') attributes and its hedonic ('non-functional' or 'non-task-focused') attributes [6, 7]. Pragmatic quality, denoting system functionality and availability, represents a product quality dimension associated with task achievement or the user's practical approach to accessing said function, so-called utility and usability aspects [7]. To assess subjective pragmatic (usability) quality, researchers have developed a range of questionnaires [8]. Pragmatic quality constitutes an essential facet of the user experience and holds significant importance [9].

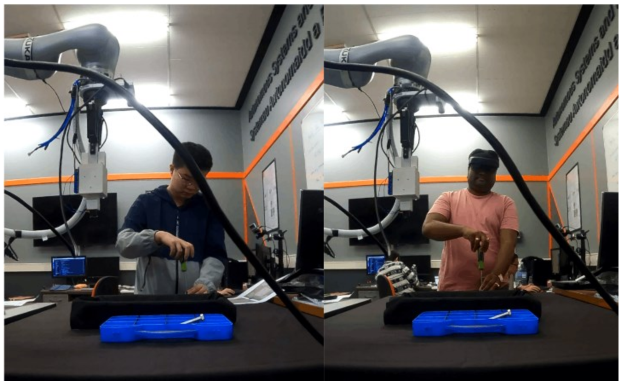
Figure 1 The image on the right shows a participant completing an HRC task with AR device, while the image on the left shows a participant completing the same task without AR device.

In assembly operations, workers must adapt to product specification variations that come in diverse batch magnitudes [10]. The predominant mode of information dissemination, typically defined by stationary and paper-based assembly directives, fails to meet these adaptability demands, leading to issues, such as cognitive strain among employees and diminished operational efficiency [11]. The emergence of augmented reality (AR) has the potential to reduce cognitive strain and improve operational efficiency [12]. AR is a technological innovation defined by its overlay of digital visuals onto physical entities or surroundings via devices, such as head-mounted displays (HMD) or portable screens [13]. It offers a profound prospect for both scholars and industrial sectors to delve into novel paradigms of data communication within the HRC framework [12].

In this paper, our study provides empirical evidence that AR significantly enhances perceived pragmatic quality in human-robot collaborative manufacturing and increases user satisfaction. It establishes a new understanding of AR's impact on assembly tasks, bridging a gap in the current literature on industrial HRC applications. Furthermore, the research introduces a novel, replicable methodology that integrates robot control, data communication, and real-time 3D visualization, offering a framework for future advancements in the field.

II. LITERATURE REVIEW

A. *HRC in Assembly*

For manufacturing, especially assembly, there emerges a necessity to swiftly adapt to unique customer preferences and to structure processes with agility [16]. Workers in these adaptive assembly systems are expected to manage an array of ever-evolving product variants that differ in batch quantity [10]. The dominant method of disseminating information, often manifested through static and paper-based assembly directives, falls short in meeting these flexibility demands. Consequently, this leads to issues such as cognitive strain on workers and diminished efficiency [11].

One piece of evidence for the potential of human-robot collaboration in remedying these challenges is provided by the work of A. Realyvásquez-Vargas et al., who integrated a collaborative robot into a manufacturing setup, with the goal of mitigating occupational hazards and enhancing efficiency [14]. Another example is the work presented by A. Cherubini et al. [15], in which the researchers devised a cooperative human-robot assembly cell for collaborative assembly tasks. Within this assembly unit, the collaborative robot oscillates between active and passive roles throughout the assembly procedure, aiming to alleviate the workload of the employee while accommodating their requirements [15]. This setup proficiently handles direct physical interactions between the robot and the operator, as well as between the robot and its surroundings.

B. *Pragmatic Quality*

As with all interactive systems, a positive user experience is essential for robots to achieve the anticipated benefits. If users feel negative towards interactions with robots, it may result in a reluctance to engage with them, which in turn could hinder the acceptance of future robotic technologies [5]. A favorable user experience underpins the widespread adoption of robots in society. Such a positive user experience does not materialize on its own but necessitates systematic design and evaluation [17]. Consequently, the user experience for robots should be at the forefront of considerations when developing such machines. According to prior studies in the realm of UX, the user experience is delineated by a system's pragmatic (often termed as 'instrumental product', 'task-focused', or 'ergonomic') attributes and its hedonic ('non-functional' or 'non-task-focused') attributes [6, 7]. Pragmatic quality can be characterized by the extent to which aspects like utility, efficiency, and ease of use are actualized, commonly denominated as usability and utility [7]. ISO 9241-11 defines usability as the "extent to which a system, product, or service can be used by specific users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use". It is worth emphasizing that usability pertains to the outcomes of system interactions. According to the definition by the ISO standard, usability is not an intrinsic attribute of the system, although appropriate characteristics of the system can facilitate usability within a given usage environment [18].

To gauge subjective pragmatic quality (usability), researchers have devised a variety of questionnaires. For instance, the System Usability Scale (SUS) developed by DEC in the UK encompasses ten items and was unveiled in 1996 [8]. Furthermore, the Technology Acceptance Model (TAM), originally designed to predict technological adoption likelihood, has been moderately adapted to function as a standardized user experience questionnaire, preserving its renowned factorial structure to measure perceived ease of use and utility [19]. In recent years, aiming to offer more succinct assessment tools, the UMUX was formulated as a brief four-item perceived usability measure with scores designed to align with the SUS [20]. For further simplification, the UMUX-Lite consists of just two items, targeting the perceived utility and ease of use [21]. It serves not only as a compact version of the UMUX but also as a condensed version of TAM [22]. Its scores exhibit a high congruence with those of the SUS [22]. This progression underscores the continuous advancements and adaptability trends in the domain of usability testing.

C. *AR Solution in HRC*

The advent of novel Information and Communication Technologies (ICT) like AR and Mixed Reality (XR) presents valuable prospects for both researchers and industries to investigate novel paradigms of HRI and HRC [12]. Hietanen et al. [23] studied the integration of depth sensors in projector-based HRC safety models, emphasizing dynamic monitoring across robot and human-centric zones. In a subsequent study by Hietanen et al. [24], the integration of an Augmented Reality Head-Mounted Display (AR HMD) was introduced, offering enhanced user interaction and a safety area visualized through the Microsoft HoloLens. Other researchers addressed challenges in the realm of augmented information for mobile robots. They proposed solutions incorporating a laser projector, AR goggles, and a handheld device [25]. Notably, the robot MAVEN showcased its movements using laser projection [25]. Tong et al. introduce an augmented reality (AR) approach that uses facial expressions to convey safety-critical messages in HRC tasks [26]. Kousi et al. presented an AR-based HRI framework designed to augment production system flexibility [27]. The framework leveraged the Microsoft HoloLens for marker-less visualization, emphasizing real-time task feedback and efficient error correction mechanisms [27]. Researchers explored AR in HRC manufacturing, introducing an AR-based Worker Support System using OpenCV and UNITY, which provides real-time guidance through camera-detected matches [28]. Another study proposed a human-robot interaction system where an operator in VR collaborates with a physical workspace counterpart, guiding robot movements through tracked interactions like red dot pointers or 3D mouse controls [29].

Based on these articles, we argue that AR-based HRC has considerable advantages in terms of user experience, efficiency, and safety compared to traditional HRC [12]. While showing significant promise in enhancing user experience, efficiency, and safety, the volume of scholarly work specifically addressing AR in HRC assembly scenarios remains limited, signifying a research gap our study aims to address.

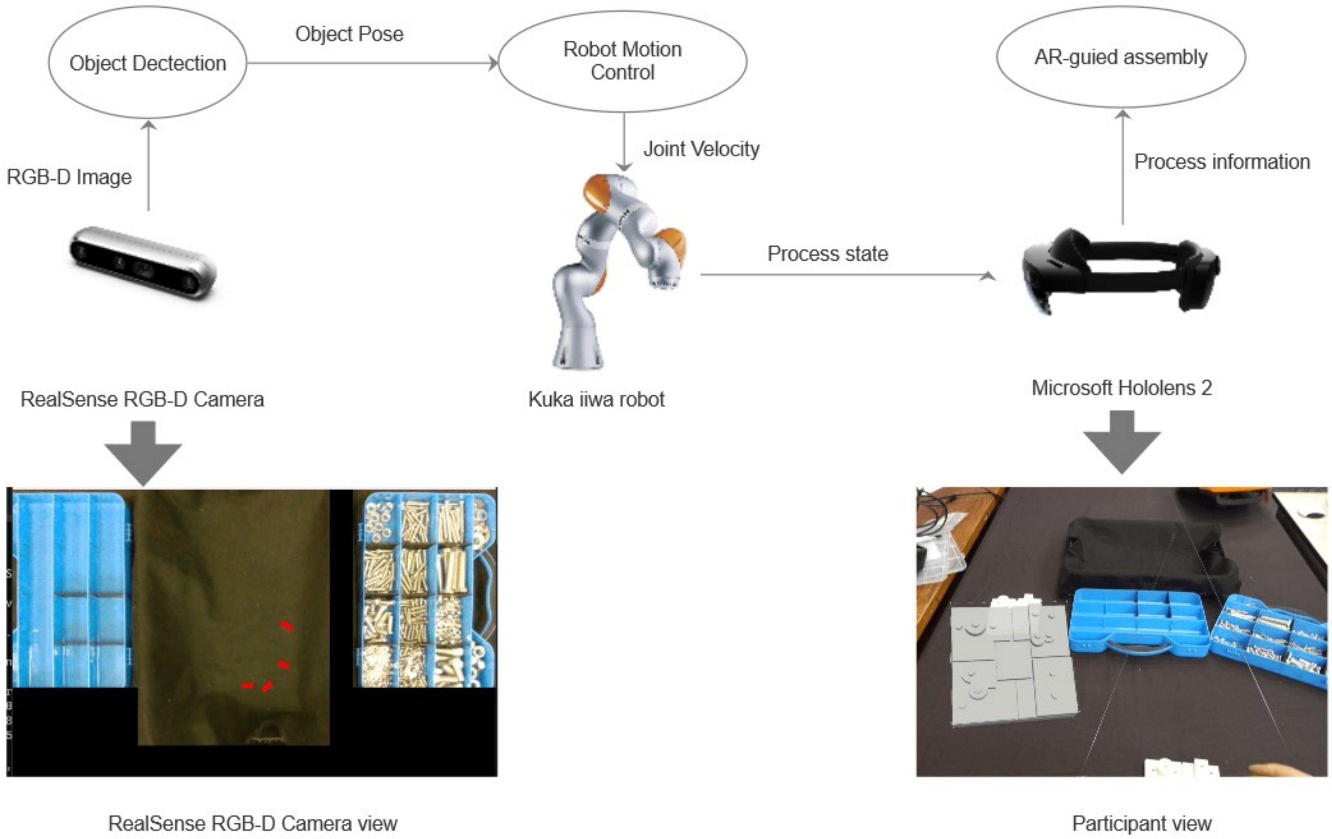

Figure 2 The AR-Guided Assembly Procedures diagram. The ellipse software blocks were developed in this system.

III. AR FOR HRC FRAMEWORK

This research adopts a multi-faceted approach integrating robot control, data communication, and Unity3D visualization (Fig. 2). The detailed methodology is described below.

A. Robot Control

In this work, we introduce an assembly task, where the operator is required to complete an assembly of a part, as illustrated in Fig 3. The part comprises of 4 components that require the user to select the screws of different sizes. In the task, the robot is responsible for picking and sorting the screws, and the user is mainly responsible for the actual assembly.

A comprehensive robot control system was developed using Python as the primary programming language. This system, based on the MATLAB, served as an integrated platform, centralizing various operations and tasks, and ensuring consistency and continuity throughout the experiments.

For screw picking and sorting, we designed our own end-effector tool attached to the robot. The end-effector tool of the robot includes an electromagnet, which is controlled via an Arduino microcontroller. This tool is capable of communicating with the control system through a serial port. The task is divided into three distinct boxes: in the first box, the robot selects the correct screws from a set of fourteen different parts. Using the magnet, it picks and sorts these screws into a central black box. The correct screws are then placed in a box closer to the user, while surplus parts are returned to the first box (as illustrated in Fig. 2). Each successful retrieval of the correct screw results in a change in the robot process state. These state changes are recorded in a global state variable, preparing the data for subsequent transmission via the User Datagram Protocol (UDP).

B. UDP Communication

In this system, efficient real-time communication facilitated by the User Datagram Protocol (UDP) is crucial for the interaction between AR goggles and the robot control system. The choice of UDP, known for its low-latency and less overhead compared to TCP, is pivotal in ensuring seamless data transfer and coordinated functioning. This communication framework, leveraging the strengths of UDP, is adept at handling the rapid exchange of information, which is essential for the responsive operation of the system. Our focus on UDP highlights its suitability for scenarios where speed and efficiency are paramount, aligning perfectly with the system's requirements for fast and reliable communication.

C. Unity3D Visualization

To achieve real-time visualization of the robot's operations, Unity3D was chosen as the development environment. Within Unity, a specialized UDP manager was developed, responsible for continuously monitoring of a specified UDP port, awaiting state messages from the robot control system.

Once the UDP manager received these state messages, it would promptly update a variable. This allows other scripts or objects within the Unity scene to react in real-time based on the robot's state, displaying corresponding animation effects or other visualization elements (see Fig. 3).

To enhance the overall system's stability, exception-handling mechanisms were incorporated at each stage. This not only ensured the timely resolution of any communication discrepancies but also fortified the robustness and stability of the system during its operational course.

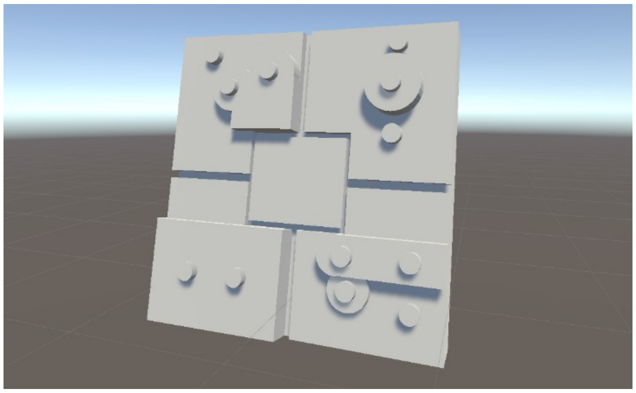

Figure 3 Assembly model view in Unity3D.

IV. METHODOLOGY

To evaluate the influence of AR-enhanced assembly procedures on pragmatic quality, we constructed a systematic experimental study. Within the framework of a collaborative assembly task, we measured the perceived pragmatic quality of human participants during their interactions with a robotic arm, an interaction either augmented by assembly procedures showcased through an AR headset or without such augmentation.

A. Hypotheses

In the context of the HRC task, we hypothesize that AR-guided assembly would enhance pragmatic quality over traditional assembly procedures. Based on our hypothesis, we anticipate observing a higher level of perceived pragmatic quality (usability quality) in AR-enhanced assembly procedures compared to those without AR-enhanced assembly.

B. Participants

We recruited 10 participants from Cardiff University, comprised of 9 males and 1 female, spanning an age range of 23 to 30 years old. No compensation was provided for their participation. Within the cohort, 5 individuals have previous exposure to robots, whereas the other 5 have no prior interaction with collaborative robots. Moreover, 6 participants have firsthand experience with AR technologies, while the other 4 were familiarized with AR solely through media outlets.

C. Design

In this study, we employed the visualization mode as a within-subject independent variable. Participants were exposed to the following two conditions:

- Interacting with AR-Guided Assembly Procedures. (HRC-W-AR)
- Interacting without AR-Guided Assembly Procedures. (HRC-WO-AR)

Consequently, each participant experienced two distinct conditions: 1) Augmented Reality (HRC-W-AR) and 2) without AR (HRC-WO-AR). The sequence of these conditions was counterbalanced among participants.

D. Procedure

The experiment was conducted in the Robotics Laboratory of Cardiff University, overseen by two of our experimenters. Participants were positioned at a designated spot in front of the robotic arm to commence the assembly task. Initially, participants read the instructions followed by signing a consent form. After reading the instructions, the experimenters provided information on the experimental procedures according to a script and collected basic demographic information, such as gender, through a brief questionnaire. Subsequently, participants were given a card (the same card was used for both conditions) displaying the end result of the assembly. Once participants verbally indicated their readiness, researchers manually initiated the robot program, with the timing of the robotic arm's movement being determined manually. In the HRC-W-AR condition, the AR guidance system would appear in front of the participants who wore AR headset, as shown in Fig 4. As the robot was in motion, the AR guidance system displayed the current pick-up screw's corresponding assembly step, allowing participants to complete the screw assembly based on the current AR information. The HRC-WO-AR condition, participants performed an assembly task without wearing an AR headset.

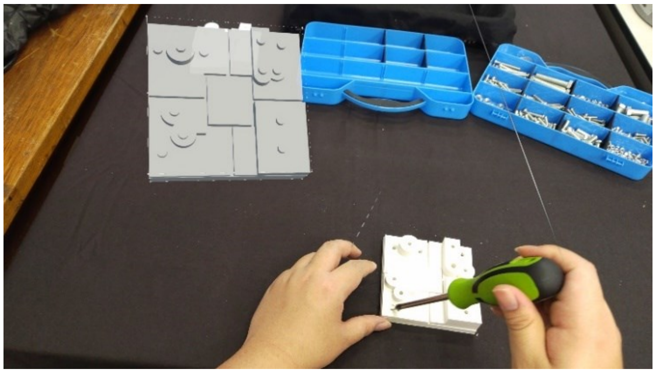

Figure 4 AR guidance system

To counteract potential order or learning effects, the sequence in which the two conditions were experienced was randomized for participants in the study. Following the completion of task, they filled out the UMXU questionnaire, as shown in Table 1. The questionnaire was based on the usability testing [17, 20]. This scale consists of 100 points, marked as follows: 0 - Strongly Disagree; 25 - Disagree; 50 - Neutral; 75 - Agree; 100 - Strongly Agree. The quantitative approach primarily focused on capturing the task success rate and task duration. The average duration of the experiment was approximately 20 minutes.

TABLE 1 UMXU FOR THE USABILITY TEST.

Usability component	Candidate UMUX item
Effectiveness	This system's capabilities meet my requirements.
Satisfaction	Using this system is a frustrating experience.
Overall	This system is easy to use
Efficiency	I have to spend too much time correcting things with this system.

V. RESULTS AND DISCUSSION

The scores from the second and fourth items, which feature negatively-frame statements, were reversely coded (by Adjusted Score = 100 - Original Score) and all scores were then aggregated to form a unified score of subjective experience.

A. Results

TABLE 2 RESULT FOR UMXU.

	HRC-W-AR		**HRC-WO-AR**		**t(26)**	***p*(1-tailed)**
	μ	**σ**	**μ**	**σ**		
Effectiveness	81	16.5	59.4	19.4	2.67	0.008
Satisfaction	71	28.2	47.8	19.9	2.20	0.02
Overall	85.6	13.3	59.3	25.1	2.91	0.005
Efficiency	82.6	15.7	55.1	28.8	2.64	0.008

T-tests were conducted on the differences between the HRC-W-AR group and the HRC-WO-AR group over four dimensions of the UMXU questionnaire, including effectiveness, satisfaction, overall usability, and efficiency. Between-group differences were significant on all four dimensions (with a significance level of $\alpha = .05$ one-tailed). The Effectiveness measure showed that users perceived the AR collaborative method with heightened effectiveness, recording an average score of 81. This was in sharp contrast to the NO-AR method, which managed an average score of 59.4. In terms of Satisfaction, the AR method was favored, registering an average score of 71. The NO-AR method lagged behind with an average score of 47.8. For Overall Usability, the findings were clear. Users leaned towards the AR method, reflecting an average score of 85.6. The NO-AR method scored lower, with an average of 59.3. Efficiency was also examined, with the AR method outperforming at a score of 82., while the NO-AR method trailed with 55.1.

B. Discussion

The juxtaposition between the AR collaborative method and the NO-AR method reveals intriguing insights that warrant discussion. First, the results from the UMXU questionnaire provide a vantage point for understanding the nuanced differences and implications of these methods in a real-world assembly setting. A stark contrast in the effectiveness, satisfaction, and overall usability scores between the two methods is evident. The AR collaborative method consistently outperformed the NO-AR method. This suggests that the integration of augmented reality in a collaborative environment significantly enhances perceived pragmatic quality. The visual cues provided by AR likely offer users more intuitive guidance, reducing cognitive load and the potential for errors.

The findings from this study have profound implications for industries and sectors that rely heavily on assembly tasks. Implementing AR collaborative methods could lead to higher quality outputs, improved pragmatic quality, and potentially reduced training time for new personnel. However, to optimize time efficiency, further research is required to understand and minimize any delays introduced by AR interactions. Moreover, the current study provides a foundation for future investigations. For instance, delving deeper into the specific components of AR that users find most beneficial or potentially exploring the long-term impacts of continuous AR usage on worker fatigue and cognitive load could be of interest.

Overall, while the AR collaborative method presents clear advantages in terms of effectiveness, satisfaction, there are avenues for further optimization and exploration. The dynamic interplay of technology and human cognition presents exciting opportunities for future research and industrial applications.

VI. CONCLUSION

The comparative analysis between the AR collaborative method and the NO-AR method illuminates the transformative potential of AR applications for human-robot collaboration in assembly tasks. Evidently, AR elevates user satisfaction and effectiveness reinforcing its promise as a pivotal tool in modern assembly and manufacturing scenarios. Furthermore, the research introduces a novel, replicable methodology that integrates robot control, data communication, and real-time 3D visualization, offering a framework for future advancements in the field. As industries evolve and seek optimization, the integration of AR technologies seems not just beneficial but imperative. This study serves as a testament to AR's capabilities, urging both academia and industry to invest further in its exploration and refinement for future applications.

REFERENCES

[1] C. Camison and A. Villar Lopez, "An examination of the relationship between manufacturing flexibility and firm performance: The mediating role of innovation," *International Journal of Operations & Production Management,* vol. 30, no. 8, pp. 853-878, 2010.

[2] R. Palmarini *et al.*, "Designing an AR interface to improve trust in Human-Robots collaboration," *Procedia CIRP,* vol. 70, pp. 350-355, 2018.

[3] E. Prati, M. Peruzzini, M. Pellicciari, and R. Raffaeli, "How to include User eXperience in the design of Human-Robot Interaction," *Robotics and Computer-Integrated Manufacturing,* vol. 68, p. 102072, 2021.

[4] M. Nordqvist and J. Lindblom, "Operators' Experience of Trust in Manual Assembly with a Collaborative Robot," in *Proceedings of the 6th international conference on human-agent interaction*, 2018, pp. 341-343.

[5] M. M. De Graaf and S. B. Allouch, "Exploring influencing variables for the acceptance of social

robots," *Robotics and autonomous systems,* vol. 61, no. 12, pp. 1476-1486, 2013.

[6] M. Hassenzahl, "The thing and I: understanding the relationship between user and product," *Funology 2: from usability to enjoyment,* pp. 301-313, 2018.

[7] T. Merčun and M. Žumer, "Exploring the influences on pragmatic and hedonic aspects of user experience," 2017.

[8] J. Brooke, "Sus: a "quick and dirty'usability," *Usability evaluation in industry,* vol. 189, no. 3, pp. 189-194, 1996.

[9] M. Hassenzahl, "The interplay of beauty, goodness, and usability in interactive products," *Human–Computer Interaction,* vol. 19, no. 4, pp. 319-349, 2004.

[10] W. Wahlster, "Semantic technologies for mass customization," in *Towards the Internet of Services: The THESEUS Research Program*: Springer, 2014, pp. 3-13.

[11] A.-C. Falck, R. Örtengren, M. Rosenqvist, and R. Söderberg, "Basic complexity criteria and their impact on manual assembly quality in actual production," *International Journal of Industrial Ergonomics,* vol. 58, pp. 117-128, 2017.

[12] M. Dianatfar, J. Latokartano, and M. Lanz, "Review on existing VR/AR solutions in human–robot collaboration," *Procedia CIRP,* vol. 97, pp. 407-411, 2021.

[13] Y. Shen, S. K. Ong, and A. Y. Nee, "Augmented reality for collaborative product design and development," *Design studies,* vol. 31, no. 2, pp. 118-145, 2010.

[14] A. Realyvásquez-Vargas, K. C. Arredondo-Soto, J. L. García-Alcaraz, B. Y. Márquez-Lobato, and J. Cruz-García, "Introduction and configuration of a collaborative robot in an assembly task as a means to decrease occupational risks and increase efficiency in a manufacturing company," *Robotics and Computer-Integrated Manufacturing,* vol. 57, pp. 315-328, 2019.

[15] A. Cherubini, R. Passama, A. Crosnier, A. Lasnier, and P. Fraisse, "Collaborative manufacturing with physical human–robot interaction," *Robotics and Computer-Integrated Manufacturing,* vol. 40, pp. 1-13, 2016.

[16] E. Abele and G. Reinhart, "Zukunft der Produktion: Herausforderungen, Forschungs-felder, Chancen. sl: Carl Hanser Fachbuchverlag, 2011," *URL:* http://www. *hanser-elibrary. com/action/showBook*.

[17] R. Hartson and P. S. Pyla, *The UX Book: Process and guidelines for ensuring a quality user experience*. Elsevier, 2012.

[18] N. Bevan, "International standards for HCI and usability," *International journal of human-computer studies,* vol. 55, no. 4, pp. 533-552, 2001.

[19] P. Silva, "Davis' technology acceptance model (TAM)(1989)," *Information seeking behavior and technology adoption: Theories and trends,* pp. 205-219, 2015.

[20] K. Finstad, "The usability metric for user experience," *Interacting with computers,* vol. 22, no. 5, pp. 323-327, 2010.

[21] J. R. Lewis, B. S. Utesch, and D. E. Maher, "UMUX-LITE: when there's no time for the SUS," in *Proceedings of the SIGCHI conference on human factors in computing systems*, 2013, pp. 2099-2102.

[22] J. R. Lewis, B. S. Utesch, and D. E. Maher, "Investigating the correspondence between UMUX-LITE and SUS scores," in *Design, User Experience, and Usability: Design Discourse: 4th International Conference, DUXU 2015, Held as Part of HCI International 2015, Los Angeles, CA, USA, August 2–7, 2015, Proceedings, Part I*, 2015: Springer, pp. 204-211.

[23] A. Hietanen, J. Halme, J. Latokartano, R. Pieters, M. Lanz, and J. Kämäräinen, "Depth-sensor-projector safety model for human-robot collaboration," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) Workshop on Robotic Co-workers 4.0*, 2018: IEEE.

[24] A. Hietanen, J. Latokartano, R. Pieters, M. Lanz, and J.-K. Kämäräinen, "AR-based interaction for safe human-robot collaborative manufacturing," *arXiv preprint arXiv:1909.02933,* 2019.

[25] D. Q. Huy, I. Vietcheslav, and G. S. G. Lee, "See-through and spatial augmented reality-a novel framework for human-robot interaction," in *2017 3rd International Conference on Control, Automation and Robotics (ICCAR)*, 2017: IEEE, pp. 719-726.

[26] Y. Tong, Q. Zhang, F. M. Galeano, and Z. Ji, "Designing an AR facial expression system for human-robots collaboration," in *2023 28th International Conference on Automation and Computing (ICAC)*, 2023: IEEE, pp. 1-6.

[27] N. Kousi, C. Stoubos, C. Gkournelos, G. Michalos, and S. Makris, "Enabling human robot interaction in flexible robotic assembly lines: An augmented reality based software suite," *Procedia CIRP,* vol. 81, pp. 1429-1434, 2019.

[28] H. Liu and L. Wang, "An AR-based worker support system for human-robot collaboration," *Procedia Manufacturing,* vol. 11, pp. 22-30, 2017.

[29] M. M. Moniri, F. A. E. Valcarcel, D. Merkel, and D. Sonntag, "Human gaze and focus-of-attention in dual reality human-robot collaboration," in *2016 12th International Conference on Intelligent Environments (IE)*, 2016: IEEE, pp. 238-241.